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1. INTRODUCTION

The U.S Navy has a strong interest in conducting atmospheric research in support of operational mesoscale forecasts used to derive atmospheric conditions deemed of strategic interest within the littoral. This effort will require relatively fine horizontal resolution (generally less than 10 km) to accurately represent the complex flow and thermodynamic conditions which typically reside near the coastal regions of the globe. The task is made even more difficult by the need to produce the required high resolution products within an operationally viable time frame. It is toward this end that the Naval Research Laboratory, in collaboration with the High Performance Computing Section of the National Oceanic and Atmospheric Administration's Forecasts Systems Laboratory (NOAA FSL), has embarked on developing a parallel version of the Coupled Oceanic Atmospheric Mesoscale Prediction System (COAMPS, Hodur 1997). The COAMPS is a nonhydrostatic fully compressible finite difference model which uses the Arakawa-C grid stagger. The purpose of this paper is to provide a brief overview of the effort to parallelize COAMPS together with two examples illustrating the naval need for parallel computational capability.

2. PARALLEL APPROACH

The initial implementation of the parallel version of COAMPS will employ the Scalable Modeling System (SMS) developed at NOAA's FSL (Hart et al. 1994, Henderson et al. 1994, Rodriguez et al. 1994). The SMS is a portable high-level library which references either internal native message passing calls and/or the standard Message Passing Interface (MPI). The SMS consists of the following three components: (i) the Nearest Neighbor Tool, which handles the domain decomposition, data exchange, and a interface to the message passing utilities; (ii) a parallel Pre-processor; and (iii) the Scalable Run-time System which provides scheduling services, name services and I/O functions. The SMS was established to provide for an efficient means of conducting parallel IO, and to minimize the changes in the initial sequential code through the use of a parallelizing pre-processor, and to allow one source code to execute on several platforms.

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3. NAVAL APPLICATIONS

Applied and research orientated projects in the littoral are two typical examples of Naval applications requiring parallel computational capability. A prime example of an applied project surrounds the use of COAMPS in the On-Scene Tactical Atmospheric Forecast Capability (STAFC). The objective of STAFC is to provide an end-to-end, on-scene, high resolution forecast capability using low-end computer hardware. The goal is to use locally available observations to improve the prediction of the atmospheric state variables in the littoral and to provide tactical weather parameters for ship self-defense (such as cloud parameters, visibility, electro-magnetic/electro-optical propagation characteristics). The primary components of STAFC consist of COAMPS, the Tactical Environmental Data Subsystem (TEDS) database server, a graphical user interface, www-based product server, and other visualization tools.

Fig. 1 shows the configuration of the system and communications links used on a test of the system aboard the USS Nimitz in June of 1997. The model required nearly 12 hours to complete a nested (55x55x20 and 52x52x20 configuration using horizontal grid spacing of 45 and 15 km, respectively) full physics 36 hour forecast on an HP750. While this particular example was run onboard a ship (we believe this to be the first time in US Naval history that a mesoscale weather forecast model was run and visualized onboard an aircraft carrier), a more typical scenario will involve running the model on a 4-8 processor computer at one of several Naval operational centers. The overall goal of the parallel development will be to insure the timely completion of the high-resolution runs for use in an operational environment without the need to sacrifice on model numerics and/or physics.

A second example of parallel development centers around research applications of complex phenomenon within the littoral. For this example we present observations and modeling results from a study of the Kaus flow over the Arabian Gulf (AG). The Kaus is a wintertime, pre-trough, moist southerly flow over the AG that can, on occasion, reach gale force strength (Perrone 1979). His depiction of the Kaus was one of a cross-isobaric flow along the Zagros mountains of western Iran (see his Fig. 3.2). The observations suggest that the strongest southerly flow typically occurs over the eastern AG as the flow responds to "channeling" along the Zagros and rapid pressure falls associated with wave-induced lee cyclogenesis over the northern AG.

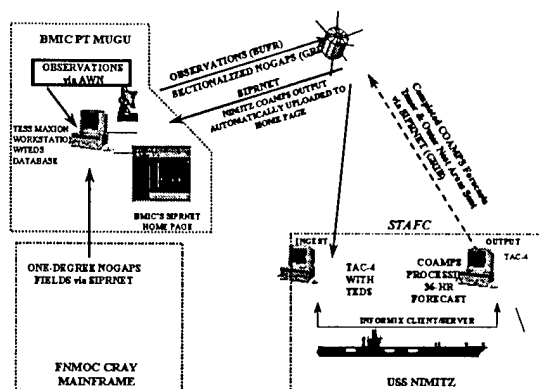


Fig. 1 Schematic diagram showing STAF configuration for the USS Nimitz test conducted in June 1997. The Figure was provided courtesy of John Cook of NRL.

More recent observational, theoretical, and numerical studies have shown that the windward slope of major mountain chains is a region conducive to the development of low-level along-barrier jets or coastally trapped surges (Griffiths and Hopfinger 1983; Dorman 1985; Pierrehumbert and Wyman 1985; Mass and Albright 1987; Burk and Thompson 1996). The dynamics of these phenomenon have been tied to Kelvin waves, relatively shallow coastally trapped density currents (1000m deep or less), and columnar disturbances which have perturbations that tend to scale with the depth of orography. The relationship of the modeled Kaus flow to these basic models of windward flow adjustment along a mesoscale barrier will be presented in Section 6.

4. SYNOPTIC CONDITIONS DURING 7-8 FEBRUARY, 1995

The time period of interest to this study covers the Kaus flow conditions that developed in the pre-trough environment between 0000 7 February and 0000 8 February 1995 (Figs. 2 and 3). The evolution of the synoptic-scale features closely follows the description of other Kaus events provided by Perrone (1979). In this case the synoptic-scale wave was accompanied by a strong subtropical jet of 80 m/s, cyclogenesis in the northern gulf region, and the development of moderate southerly flow near the surface ahead of an advancing cold front (Fig. 3). The flow throughout the troposphere in the Gulf region was generally from the west/southwest in advance of the middle-level trough except near the surface where an along-barrier south-southeasterly flow became established on the windward slope of the Zagros (Fig.3). Special ship observations (Fig. 4) taken over the eastern portion of the gulf between 0700 and 0800 UTC reveal the along barrier flow took the form of a low-level jet of 14-18 m/s located within the marine atmospheric boundary layer near 250m AGL. The presence of the jet is also

captured at a similar level in the surface-based rawinsonde released just upwind of the AG (Fig. 5).

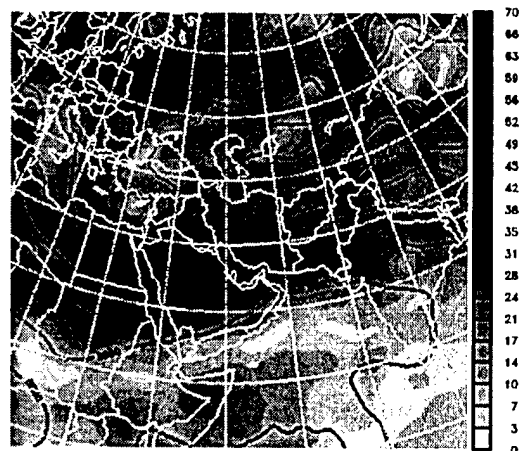


Fig. 2. NOGAPS 500mb geopotential height (dashed lines) and wind speed (shaded area) analysis for 1200 UTC 7, Feb 1995.

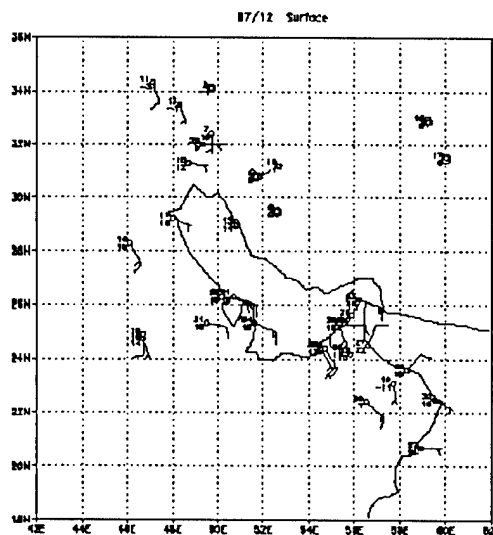


Fig. 3 Surface observation at 1200 UTC 7 Feb 1995.

5. EXPERIMENTAL DESIGN

The model results for this case were generated using the atmospheric component of the Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) (see Hodur 1997 for a complete description of COAMPS). The simulation was initialized with NAVY's global model analyses at 0000 UTC 7 February 1995 with enhancement from the available rawinsondes, pibal, satellite winds and SSM/I winds data and run for a 24 hour period chosen to capture the evolution of the pre-frontal Kaus flow over the Persian Gulf. The NOGAPS 12 and 24 hour forecasts from the initial time were used as the lateral boundary conditions using a Davies (1976) nudging condition. For this initial simulation, moisture was treated as a passive tracer.

A fixed 3:1 ratio was used to define the grid spacing

(108, 36, 12 km) between the three one-way interacting nests used in the simulations. A stretched vertical coordinate was used to vary the vertical resolution from 20 m near the surface to a maximum of 750 m in the lower stratosphere. The model top was placed at 22 km. The topography (see Fig. 6) for all experiments was obtained from the Navy's 1 km global data base. The soil moisture and temperature profiles were derived from the lowest atmospheric analysis and the Navy's global climatological data base.

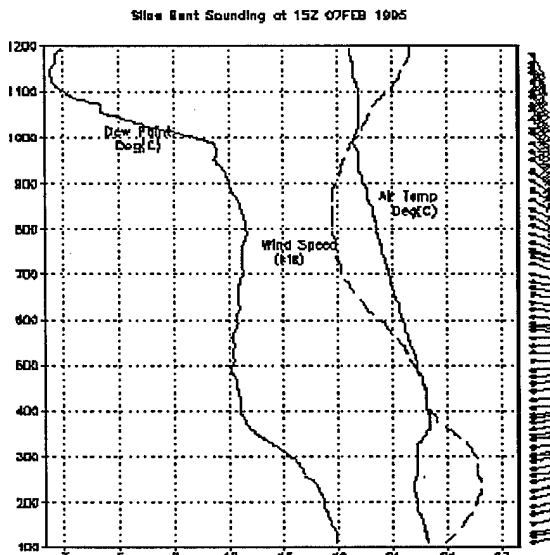


Fig 4. 1500 UTC 7 Feb., 1995 radiosonde released over the Persian Gulf from the ship Silas Bent. The location of the ship is marked as a solid dot in Fig. 4.

6. MODEL RESULTS

a. Low-level regional-scale flow and thermodynamic structure

Plots of the low-level flow, thermal structure, and moisture fields are shown in Figs. 7a,b for a 24 hour period covering the pre-trough period when a predominantly southerly Kaus flow existed over the Persian Gulf region. The evolution in the moisture field shows that parcels residing or passing through the Persian Gulf region had three primary source regions consisting of; (i) dry drainage flow off the Hajar and Zagros Mountains, (ii) moist marine air passing through the straits of Hormuz, and (iii) a mixture of continental and marine air passing over southern Saudi Arabia along the western flank of the Hajar mountains. Further moistening of this southerly air stream occurred as a result of evaporation over the relatively warm Gulf waters. This resulted in low-level mixing ratio values over the Gulf of 10 to 15 g/kg between 0000 and 1500 UTC (Figs. 5b-c) which corresponds well with the values obtained from the ship rawinsonde shown in Fig. 4.

After 1200 UTC (Fig. 7a) the narrow moisture plume

spread rapidly northward in a manner similar to the descriptions of the coastally trapped moist surges that occur along the west US coast (Mass and Albright 1987). The surge was confined within a Rossby radius of deformation of the Zagros and maintained a steady propagation of approximately 12 m/s for the entire simulation before finally passing out the northern boundary of the nest near 0000 UTC on the 8th (Fig. 7b)

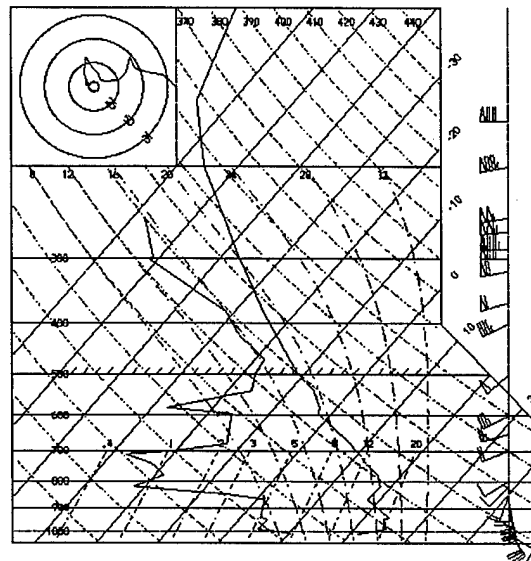


Fig. 5 Skew-T at 0000 UTC 8 Feb, 1995. Sounding location is given by the + sign in Fig. 6.

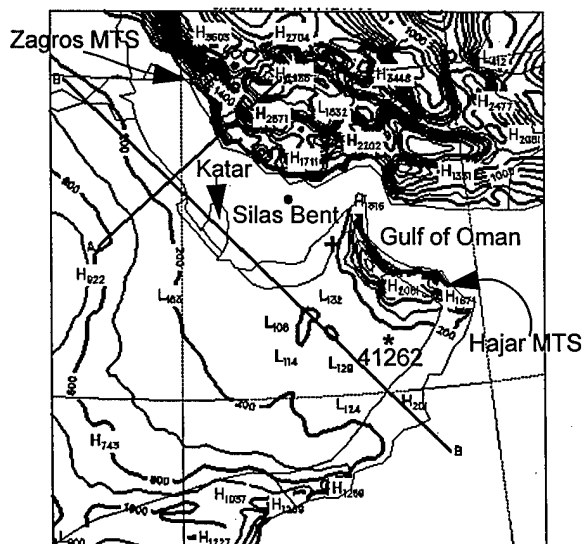


Fig 6. Terrain height plot of COAMPS grid 3 (contour interval is 200 m). The solid lines mark the cross section locations shown in Fig. 7 and 8. The dot indicates the ship location shown in Fig. 3. The cross indicates the surface data location shown in Fig. 9.

The model results suggest that the moisture source over the AG emanating from the interior region of southern Saudi Arabia had its origin in the inland penetration of the marine layer along the southern Arabian coast. By 1200 UTC, the sea breeze circulation had penetrated inland approximately 150 km forming a convergence zone over 500 km in length. Further inland penetration occurred with the onset of nocturnal cooling as drainage flows developed on the northern slope of the Omani mountains and began to advect the residual moisture northward with time.

As the cooling intensified, the drainage flow ultimately took on a density current structure with a well defined leading edge gradient in the thermal, moisture, and wind fields (Figs. 7b and Fig 8b). The current was approximately 1 km deep, propagated northward at approximately 15 m/s, and had peak frontal relative speeds of 1 to 5 m/s [15-20 m/s ground relative flow]. By 0000 8 February (Figs. 7b and 8b), the density current had propagated northward into a broad valley that extends southwestward from Katar (see Fig. 6). Diurnal heating over the interior deserts during the day acted to mix this moisture upward to a level of approximately 2 km. This process effectively altered the EM/EO characteristics over the AG as the elevated mixed layer propagated northward over the water with time.

This general sequence in the model moisture evolution is supported by surface observations taken in the interior of Saudi Arabia west of the Hajar mountains which shows a similar diurnal trend in the wind, temperature, and moisture fields over a 60 hour cycle (Fig.10). Given the quiescent nature of the winter-time flow in the region, we suspect that the sequence of events just described is rather common and may thus play a dominant role in determining the wintertime characteristics of the flow and moisture fields over the Gulf. The role of this flow in the formation and maintenance of the along-barrier surge evident in Figs. 7 and 8 is described in the next section.

c. The Kaus

The modeled moisture surge originated near a region of low-level convergence over the southern AG. This convergence zone formed between the drainage flow off the Zagros mountains and the merger of the two air currents which resulted from a split in the low-level southerly flow about the north/south orientated Hajar mountains. The convergence was particularly strong owing to the acceleration that occurred in both currents upwind from the Gulf and the large directional differences between the currents as they met in the lee of the Hajar mountains.

The large directional differences between the two currents resulted, in part, to the forcing of the local orography as the flow was channeled toward the west after passing through the narrow Straights of Hormuz. The

cyclonic/anti-cyclonic turning in the eastern and western branches of the split flow in the lee of the Hajars is also indicative of the response one would expect from low Froude number ($Fr=U/NH$) flow about an isolated barrier. Taking a low-level average of the winds (10 m/s) and stability ($.01 \text{ s}^{-1}$) over the lowest 1000m and using representative terrain height of 2000 m generates a local Fr number estimate of approximately 0.5 at 0600 UTC which is in the range where we expect significant low-level blocking, flow splitting, and the presence of lee vortices (Smolarkiewicz and Rotunno 1989).

It is interesting that the numerical solutions of low Fr number flow about more isolated peaks also contain jet like structures that initially form along the flank of the barrier and which can extend well into the lee (see Fig. 1 of Smolarkiewicz and Rotunno 1989). For finite mesoscale barriers such as the Hajars, these regions of acceleration about the flank may become particularly strong as the flow first becomes blocked along the upwind portion of the barrier forming a strong along barrier jet (Fig. 6b). Such a jet was evident in the first six hours of the simulation and again after 1800 UTC as the lower layers stabilized due to nocturnal cooling and the passage of the density current. The presence of this jet is corroborated by the sounding data presented in Fig. 5.

d. surge evolution

After its formation, the surge moved at a uniform speed of approximately 12 m/s up the coast of Iran. This was considerably slower than the speed of the maximum winds within the surge indicating that there was a system relative speed toward the leading edge. Model derived soundings taken over the central Gulf in the pre and post-surge air masses (not shown) also reveal that the wind and thermal perturbations associated with the surge were confined vertically to within a 1000 m of the surface and further indicate that the depth of the cooling remained fairly constant well after the leading edge had passed. Given these characteristics, and the fact that the perturbations in the thermal and flow fields associated with the surge did not scale well with the overall height of the Zagros (3 km), suggests that the dynamics of the feature relate more closely to density current models proposed by Mass and Albright (1987) than the columnar disturbances discussed by Pierrehumbert and Wyman (1985).

The surge remained tied to the low-level baroclinicity associated with sloping MABL throughout the entire simulation. Vertical cross-sections taken normal to the surge axis (Fig. 9) show that a distinct jet core developed within the surge over the eastern Gulf. This appears to be a characteristic feature of laboratory generated gravity currents confined to travel along a fixed boundary in a rotating fluid (Griffiths and Hopfinger 1983). While diurnal forcing modified the slope of these surfaces somewhat, a

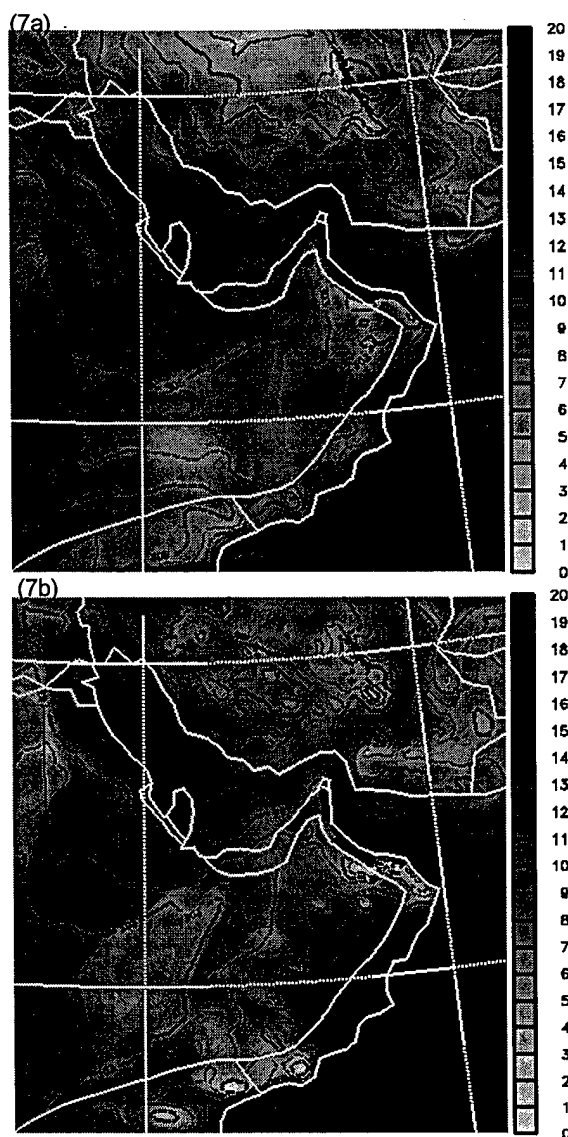


Fig. 7 COAMPS 12 and 24 hour forecast of horizontal mixing ratio (shaded area) and potential temperature (dotted lines, every 3 K) at 200 meter height valid at (a) 1200 UTC 7 and (b) 0000 UTC 8 Feb., 1995.

sensitivity case run without radiation, reproduced this feature at nearly the same magnitude. This suggests that the current was driven primarily by the dynamics resulting from the adjustments to gravity in a rotating fluid.

7. Summary

A brief overview the approach used in the parallel development of the NRL COAMPS was presented. Two examples of the naval need for a parallel mesoscale model were also discussed. Results from a high-resolution model simulation initialized with real data were presented for a pre-trough southerly Kaus flow over the Arabian Gulf region. The purpose of the case study was

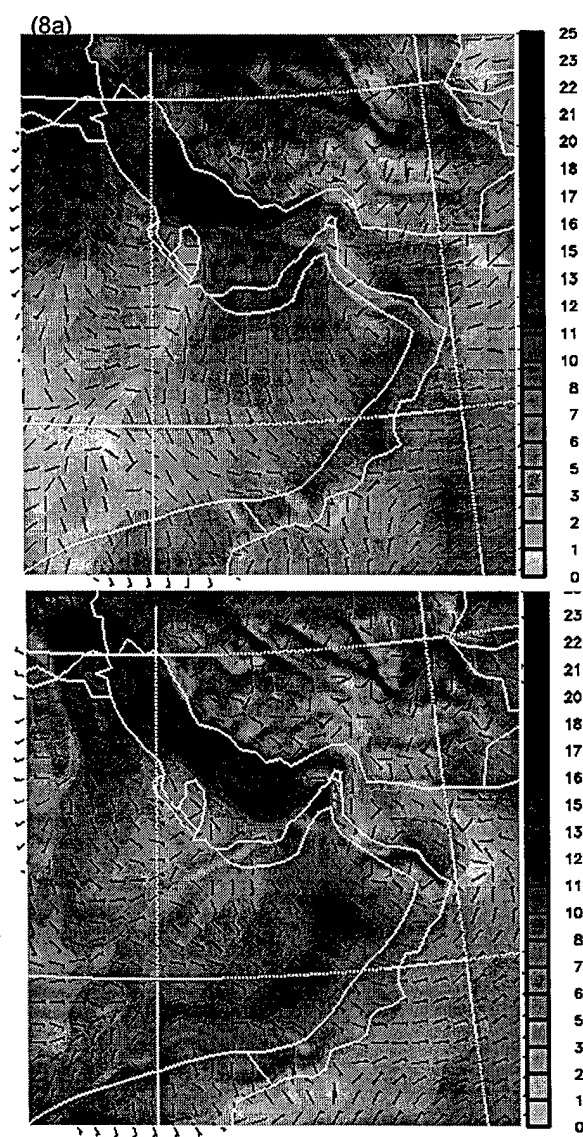


Fig. 8 COAMPS 12 and 24 hours forecast of the horizontal wind speed (shaded area) and wind barb (m/s) at 200 meter height valid at (a) 1200 UTC 7, and (b) 0000 UTC 8 Feb., 1995. The wind barbs are plotted every 6 grid points.

to document the distribution of the low-level moisture fields over the AG which have a strong impact the EM/EO propagation in the region. The results indicate that the low-level moisture over the Gulf was strongly modified by diurnal heating/cooling cycle that lead to a moist density current over the interior regions of southern Saudi Arabia and the formation of a narrow coastally trapped surge that formed over the eastern Gulf. The surge was initiated as low Froude number flow about the Hajar mountains located upwind from the Gulf led to low-level blocking, flow splitting, and strong vorticity generation in the lee of the barrier. The surge had many characteristics of the surges that occur along the west coast of the US including the overall properties of a density

curent. The surge also contained a low-level jet of 20 m/s which formed over the eastern Gulf. This is consistent with the descriptions of the stronger flow occurring over the eastern Gulf by Perrone (1979) and is also a noted feature of density currents confined to move along a fixed barrier in rotating tank experiments Griffiths and Hopfinger (1983). The mesoscale variability in the low-level thermal, moisture, and flow fields over the Gulf that resulted from these various processes underscores the need for high-resolution prediction in the littoral in order to accurately predict the state variables and their impact on the EM/EO characteristics over this most vital region.

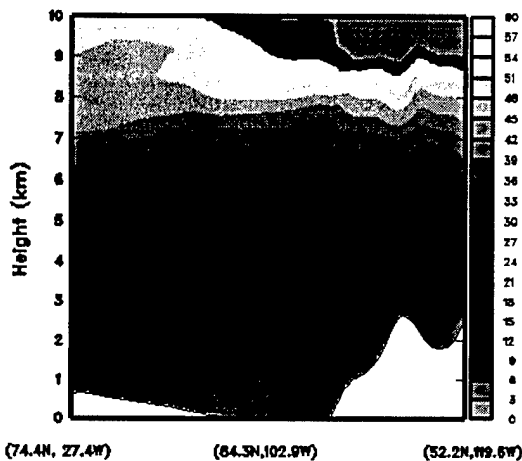


Fig. 9 Cross section A (position shown in Fig. 4) analysis of wind speed (m/s, shaded area) at 1800 UTC 7 Feb., 1995.

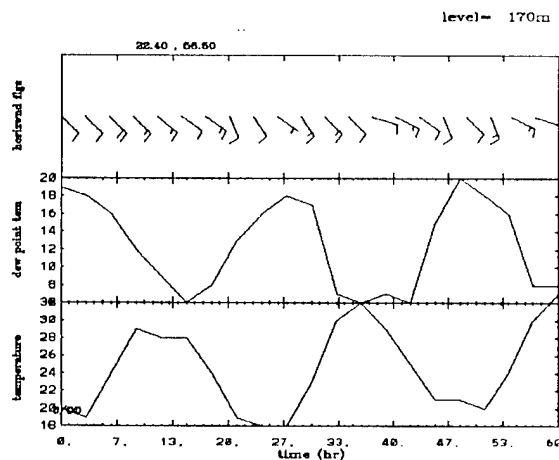


Fig. 10 Observed wind (full barb = 5 m/s), temperature (C), and dew point temperature (C) from the surface station 41262 marked as a + in Fig. 4. Figure denotes the time in hours from 0000 UTC 6 to 1200 UTC 8 Feb., 1995 with 3 hourly time interval.

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